Revista Brasileira de Geofísica; 1987, Vol. 5, 173-188

doi: 10.22564/brjg.v5i2.2238

HEAT FLOW INVESTIGATIONS IN EUROPE: DATA COMPILATION, HEAT FLOW MAP AND ITS INTERPRETATION

VLADIMÍR CERMÁK

Geophysical Institute, Czechoslovak Academy of Sciences, 141-31 Praha 4, Bocni, II/1a, Czechoslovakia

Proofs are to be sent to:

RNDr. Vladimír Cermák, Geophysical Institute, Czechosl. Acad. Sci., 141-31 Praha 4, Bocni, II/1a, Czechoslovakia

The knowledge of the regional distribution of heat flow density on the Earth's surface represents an essential boundary constraint for any interpretation of geophysical and geological data. With the use of more than 3000 published heat flow data, a heat flow map of Europe (1:5,000,000) was prepared in 1979. This map is now being revised and a new version is scheduled to appear in 1988. The present stage of the preparation is briefly discussed with special attention paid to the construction principles and representation of heat flow anomalies of different sizes. The map of the surface heat flow was supplemented with the crustal thickness pattern, data on crustal radioactivity, thermal conductivity and other available information on heat flow — tectonic age, heat flow — heat generation, and heat flow — crustal thickness relationships. On the basis of this material deep temperature distributions within the crust and the lithosphere were calculated for one-dimensional and two-dimensional models. By a conversion of the seismic velocities to heat generation data the preliminary pattern of the Moho heat flow was projected. The Mohorovicić discontinuity is clearly not an isothermal surface, neither is the ouflow of heat from the upper mantle constant, but both parameters may vary in broad ranges. By equating the depth at which the deep temperatures intersect a mantle solidus, heat flow pattern was used to assess the regional variation of the lithospheric thickness on a continental scale.

O conhecimento da distribuição regional de densidade de fluxo térmico sobre a superfície da Terra representa uma condição de contorno essencial para qualquer interpretação de dados geofísicos e geológicos. Utilizando mais de 3000 dados publicados de fluxo térmico, um mapa de fluxo térmico da Europa (1:5.000.000) foi preparado em 1979. Este mapa está sendo revisto no momento e uma nova versão deve ser publicada em 1988. O estágio atual da sua preparação é discutido, prestando atenção especial aos princípios de construção e representação das anomalias de fluxo térmico de diferentes dimensões. O mapa de fluxo térmico superficial foi suplementado com o padrão de espessuras crustais, dados sobre a radioatividade crustal, condutividade térmica, e outras informações disponíveis sobre fluxo térmico. — relações entre idade tectônica e fluxo térmico, entre produção de calor e fluxo térmico, e entre fluxo térmico e espessura crustal. Com base nesse material, distribuições de temperatura em profundidade no interior da crosta e da litosfera foram calculadas com modelos uni e bi-dimensionais. Através de uma conversão de velocidades sísmicas em dados de produção de calor, foi feita uma projeção do padrão de fluxo térmico na Moho. A descontinuidade de Mohovicic não é claramente uma superfície isotérmica, nem o fluxo térmico proveniente do manto é constante, e ambos os parâmetros podem variar em uma faixa ampla de valores. Através da determinação da profundidade na qual as temperaturas profundas interceptam a curva solidus do manto, o padrão de fluxo térmico pode ser utilizado na determinação das variações regionais da espessura da litosfera, em uma escala continental.

(Traduzido pela Revista)

INTRODUCTION

The terrestrial heat flow, even though a quality apparently negligible (60-80 mWm^{-2}), is definitely the most powerful surface manifestation of the Earth's internal energy. The seismic or volcanic activity, which from time to time may be fatal to thousands living in the afflicted region, represents less energy released per unit time than that which is being continuously transported by heat towards the Earth's surface (in total $4x10^{13}$W). This outflow of energy from the deep interior determines the Earth's internal temperature field and reflects the deep-seated tectonic processes. Its knowledge is thus very important in geophysics and geology and provides a useful research tool for studying the crustal and lithospheric structures and helps to understand the nature of their evolution.

It is now almost half a century since the first terrestrial heat flow measurements were made and it will be soon a decade since the first attempts were made to construct regional heat flow patterns on a continental scale. Remarkable progress in heat flow studies in the sixties and early seventies compelled the urgent need of a map which would show the distribution of heat flow density on the tectonic background. This need was further accelerated by the world-wide search for exploitable sources of geothermal energy. As the geothermal areas are characterized by elevated heat flow both on the regional and local scales, the heat flow pattern may make a considerable contribution to recognizing and identifying the suitable resources, and to enhancing the development of individual sites of geothermal potential.

Realizing the global diversity of data and publications the IUGG established in 1975 a Working Group within the International Heat Flow Commission, the purpose of which was to help consolidate heat flow data. Special attention was paid to coordinating the efforts of researchers to construct a heat flow map of Europe. The preliminary 1:5,000,000 heat flow map of Europe was presented during the IASPEI/IAVCEI Assembly at Durham in 1977 (Cěrmák & Hurtig, 1977). On the basis of many valuable suggestions and due to joint cooperation of numerous co-workers the final multi-colour map appeared in 1979 (Cěrmák & Hurtig, Eds. 1979) as a part of a comprehensive monograph describing the results of heat flow researches in practically all European countries (Cěrmák & Rybach, Eds., 1979).

Since then a number of papers have appeared interpreting the European heat flow pattern in terms of the crustal structure and tectonic evolution. The heat flow field was correlated with the seismic, gravity and magnetotelluric data, with the distribution of the near surface radiogenic heat production and was used for the projection of the deep temperatures. A critical assessment of all data and a compilation of the new results have been carried on step forward. The idea to construct similar heat flow maps of other continents became a current programme of the IHFC, including also the preparation of the new heat flow map of Europe. This paper briefly discusses the heat flow map of Europe, summarizes the main construction principles used, and gives a few examples of the use of the continental heat flow pattern in basic geophysical research.

HEAT FLOW DATA AND THEIR DISTRIBUTION

To be able to use the results of the individual heat flow measurements for further regional studies, we are in need of a map showing the surface distribution of heat flow density. To meet this requirement, in principle two ways may be recommended: (i) a functional representation of the heat flow field together with contour maps based on calculated trends or a harmonic analysis of a convenient order, (ii) a statistical correlation of the geothermal activity with the tectonic setting complemented with isolines of the heat flow drawn in a simplified tectonic map of the area under investigation. The latter method was used in the preparation of the heat flow map of Europe.

The construction of the map was based on a total of 3076 data, the geographical distribution of which is shown in Fig. 1. In spite of the relatively great number of heat flow observations in many countries, the density of data is still far from being uniform or sufficient, and from large territories data are missing or only preliminary information is available. All the heat flow data avaiable in Europe at present are summarized in Table 1 (see also Fig. 2). In comparison with a similar table published earlier (Cěrmák,, 1979), only heat flow values published together with their coordinates and with additional information were considered. To satisfy the requirements of the world heat flow data catalogue, which is under preparation, all data were critically reassessed and rated into several categories. As reliable data, i.e. A and/or B category, we understand data of up to ± 10% or ± 20% uncertainty, respectively, according to the particular author's estimation. Heat flow data less reliable (C-category), heat flow estimates, data clearly disturbed by transient effects or data without sufficient detailed information were excluded. For the actual construction of the map, however, in addition to the published heat flow data, other suitable geothermal information such as deep temperature measurements, bottom hole temperatures, geothermal gradients and subsurface temperature maps were used. If local heat flow maps were available, these were incorporated into the large-scale final map. All the above information was used as check points and then extrapolated on the basis of the regional tectonic setting.

Heat flow density generally decreases from younger to older tectonic units and the units of the same tectonic history are to some extent characterized by similar heat flow values. With the knowledge of the age of the latest tectonic-thermal event, the characteristic surface geothermal activity can be predicted (Chapman & Pollack, 1975). For the construction of the heat flow map of Europe the results of the correlation between the heat flow and the tectonic age were used. The course of isolines in areas with no direct observations was correspondingly adapted to follow the boundaries of principal tectonic units.

HISTOGRAM OF HEAT FLOW DATA

Fig. 3 shows the updated histogram of all heat flow data in Europe, with subdivisions into land and marine data. The mean value for land measurements is 66.4 mWm^{-2} (n = 2394 data, data from Iceland,

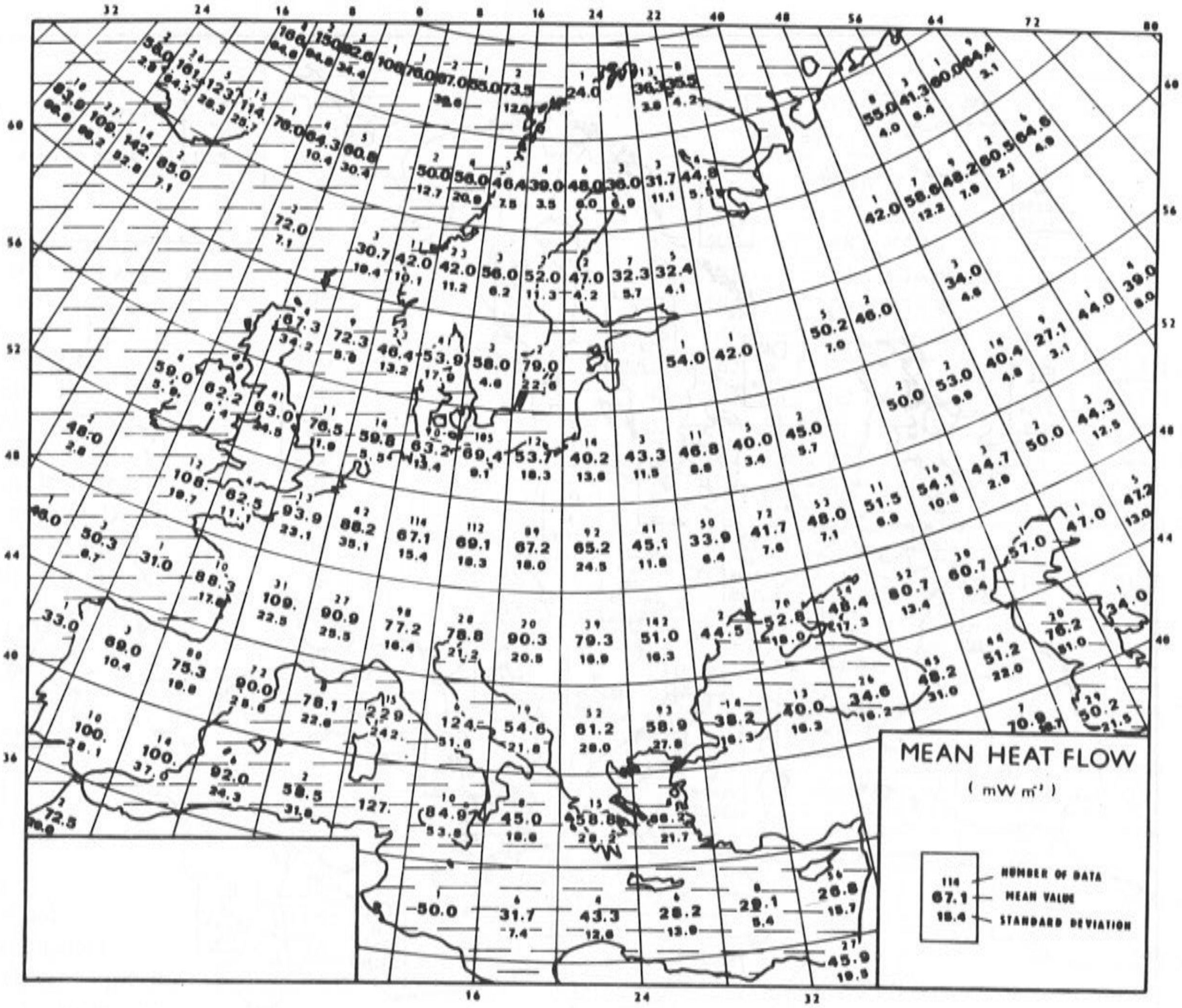

Figure 1 — Number of heat flow data, mean heat flow value and its standard deviation in a 4°x4° geographic grid in Europe.

Cyprus and Israel being excluded), the mean for 728 reliable data is 66.7 mWm^{-2}. The marine data given in Table 1 only supplemented the map in adjacent sea regions and their mean (80.5 mWm^{-2}, n = 757), as well as their frequency distribution should not be considered as generally valid.

PREPARATION OF THE MAP, DATA CORRECTION PROBLEMS

The geographical distribution, the density, as well as the quality of data are uneven and in many cases the proposed interpretation of the observed data and the isoline pattern is neither definite nor unambiguous. To minimize the subjective standpoint of the compilers, several working versions of the map were prepared in the period 1975-78 and distributed to specialists all over Europe for their comments and criticism. Each consecutive version was thoroughly reworked with consideration of the remarks presented. New data obtained later were also incorporated during this procedure.

As the distribution of the geothermal activity is closely connected with the tectonic development of the Earth's crust, the isolines of the heat flow were drawn over the schematic tectonic pattern. For this background map the simplified and 1:2 reduced International Tectonic Map of Europe (Anonymous, 1962) was used supplemented with some information by the Geological Map of Europe and the Mediterranean Area (Anonymous, 1971). The distribution of deep faults was adopted after the map prepared by Grumbt et al. (1976).

Such geological phenomena as sedimentation, erosion, uplift, etc. as well as the effect of the past climatic changes may influence the observed heat flow to a greater or lesser extent. In further studies and in the comparison of the geothermal activity of various tectonic provinces, attention should be paid to these perturbations and reasonable regional corrections should be evaluated. However, such a procedure has to be applied on large territories and requires both uniform approach and detailed knowledge of the local geological history. For the present state of the investigation and for the construction of the map, preference was given to "uncorrected" values rather than to introduce something that might be a subjective standpoint. This criterion has nothing to do with the application of technical corrections, such as for local topography, conductivity contrast, borehole inclination, etc. used by individual authors.

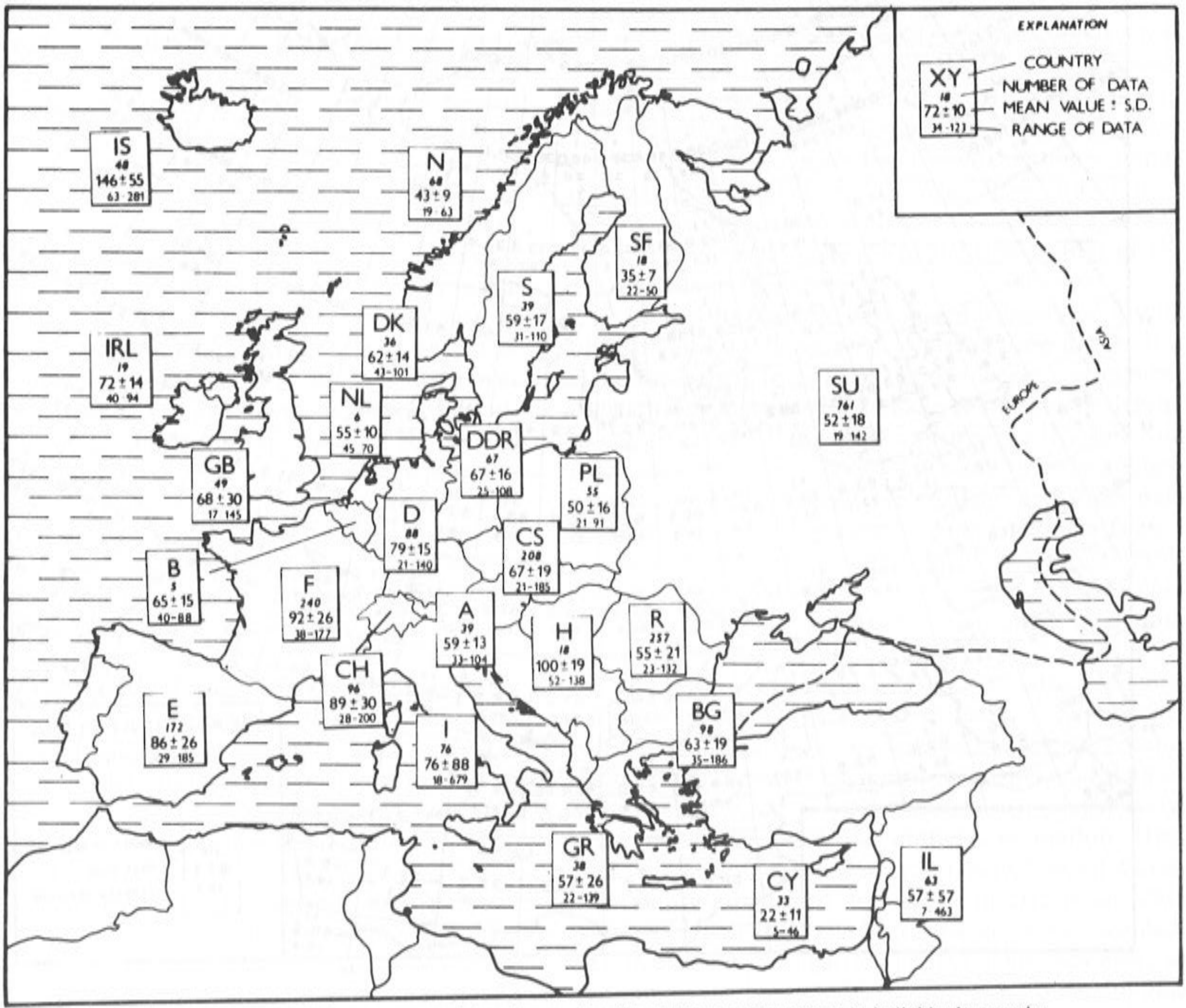

Figure 2 — Map of Europe summarizing the results of heat flow measurements in individual countries.

The heat flow, especially in Cenozoic depressions such as marginal foredeeps, intramontane and neotectonic basins, as well as in outskirt and internal seas, may be considerably affected by non-equilibrium factors of intensive sedimentation. The heat flow value may be underestimated by 10-50% in comparison with the equilibrium value. In some case, when the sedimentation rate may have reached as much as 30 cm/1000 years as in the Black Sea, the proposed corrections for rapid sedimentation amounted to 50-100% (Erickson, 1970). On the contrary, uplift and erosion apparently raise the measured value of the heat supply from the depth. This effect was calculated e.g. for several Alpine lakes (Haenel & Zoth, 1973) and a negative correction of about 30% of the measured heat flow was obtained.

Climatic changes during the past and especially the retreat of the continental ice sheet at the end of the Pleistocene affected the underground temperature field and a certain correction is to be added to the present observed value. This problem may not only be specific for areas which were glaciated in the past, but some effects of recent surface temperature changes may have influenced the present underground temperature field even in regions far from the southern rim of the former continental glacier (Ciaranfi et al., 1973). However, the amount of the paleoclimatic correction usually does not exceed a few percent of the measured heat flow (Cĕrmák, 1977) and is relatively constant over large areas, so its application will not greatly affect the surfaces heat flow pattern.

It is almost certain that for most of the European area (except for the southern geologically young regions framing the Mediterranean Sea) the amount of particular corrections to the measured heat flow will be either small or negligible and that their application would not change the proposed heat flow map too much. Nevertheless, the present proposed heat flow field based on measured (i.e. uncorrected) values has to be considered carefully in areas of young geological history.

HEAT FLOW PATTERN

The heat flow pattern as shown on the map (Fig. 4) may be described by two components: (i) the regional part, and (ii) the local part of the observed surface geothermal activity. On the whole, the regional heat flow field is dominated by a general "north-east" to "south-west" increase, which seems to be an obvious consequence of the continental tectonic evolution. The major heat flow provinces correlate relatively well with the principal tectonic units of the East European Plat-

Table 1 – Statistics of the observed heat flow values in Europe

Country/Area	Number of Measurements	Number of Data	Heat Flow, mWm^{-2} All data		Unreliable Data Excluded	
	N	n	Range	Wean s.d.	n	Mean s.d.
Austria	58	39	33 – 104	58.8 ± 12.7	18	61.1 ± 17.2
Belgium	5	5	40 – 88	64.5 ± 14.5		
Bulgaria	98	98	35 – 186	63.0 ± 19.4		
Cyprus	33	33	5 – 46	22.3 ± 11.3	19	25.9 ± 9.3
Czechoslovakia	246	208	21 – 185	67.0 ± 19.1	158	65.9 ± 15.8
Denmark	36	36	43 – 101	62.1 ± 13.8	6	71.5 ± 8.2
Finland	18	18	22 – 50	35.1 ± 6.9	18	35.1 ± 6.9
France	240	240	38 – 177	92.3 ± 26.1	56	95.3 ± 19.8
German Dem. Rep.	101	67	25 – 108	67.2 ± 16.1	65	67.6 ± 16.2
Germany, Fed. Rep. of	153	88	21 – 140	79.1 ± 14.9	49	73.3 ± 14.0
Greece	40	38	22 – 139	56.8 ± 26.1		
Hungary	18	18	52 – 138	100.3 ± 19.4	14	102.8 ± 16.8
Iceland	48	48	63 – 281	146.2 ± 54.7		
Ireland	19	19	40 – 94	71.5 ± 13.9		
Israel	63	63	7 – 463	56.8 ± 57.1		
Italy	108	76	18 – 679	76.0 ± 88.2	36	56.1 ± 31.9
Netherlands	6	6	45 – 70	55.1 ± 9.5		
Norway	94	68	19 – 63	42.6 ± 8.7	68	42.6 ± 8.7
Poland	55	55	21 – 91	50.2 ± 16.3	36	50.3 ± 17.9
Romania	257	257	23 – 132	54.5 ± 20.6	62	57.0 ± 28.0
Spain	172	172	29 – 185	85.7 ± 28.2		
Sweden	78	39	31 – 110	58.8 ± 16.5	36	58.0 ± 14.0
Switzerland	154	96	28 – 200	89.1 ± 30.0	73	87.3 ± 29.7
United Kingdom	83	49	17 – 145	67.6 ± 29.9	33	75.0 ± 30.7
USSR (Eurpean part) +	761	761	19 – 142	52.3 ± 17.7		
Atlantic Ocean	188	188	0 – 442	88.3 ± 71.5		
Mediterranean Sea	373	373	–2 – 921	97.6 ± 76.0		
Black Sea	196	196	–73 – 208	40.5 ± 22.8	188	41.5 ± 14.6

+ New heat flow data compilation is under preparation, but not available yet. Information given here is from 1979.

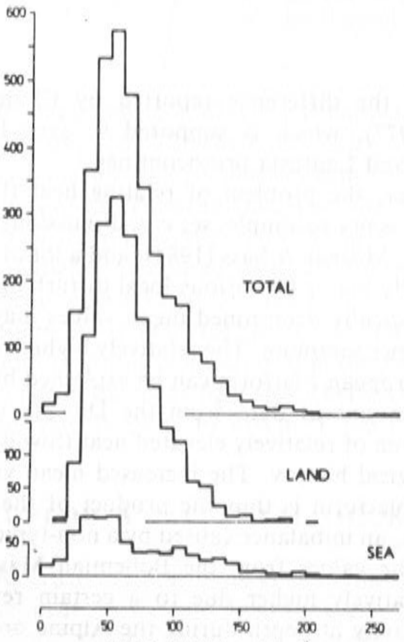

Figure 3 — Histogram of European heat flow data.

form (Precambrian craton), and Caledonian, Variscan (Hercynian) and Alpine fold belts (Fig. 5). The geothermal fine structure (local part) superimposing the regional part is mainly controlled by local tectonics, especially by the distribution of the deep reaching fracture zones and by the hydrogeological parameters.

The first order heat flow lows (< 40 mWm^{-2}) cover most of the East European Platform including both the Baltic and the Ukrainian shields, i.e. the greater part of the oldest and most stable portion of the whole continent. Other heat flow lows include smaller units such as the Bohemian Massif, the Moesian Plate, etc., representing stable, consolidated segments as well. Low heat flow is also typical of the Eastern Mediterranean Sea, probably the part of the African plate, with thick stable mafic crust, and the Black Sea. Geothermal highs (over 80 mWm^{-2}) are found in Iceland and its vicinity (part of the Mid-Atlantic Ridge system), the Rhinegraben, the Alps, the Pannonian Basin, several locations in the Balkans, Turkey and in the Caucasus, all geologically young structures, tectonically still alive or recently active, and in the Western Mediterranean and Aegean Seas, areas of thin subcontinental crust.

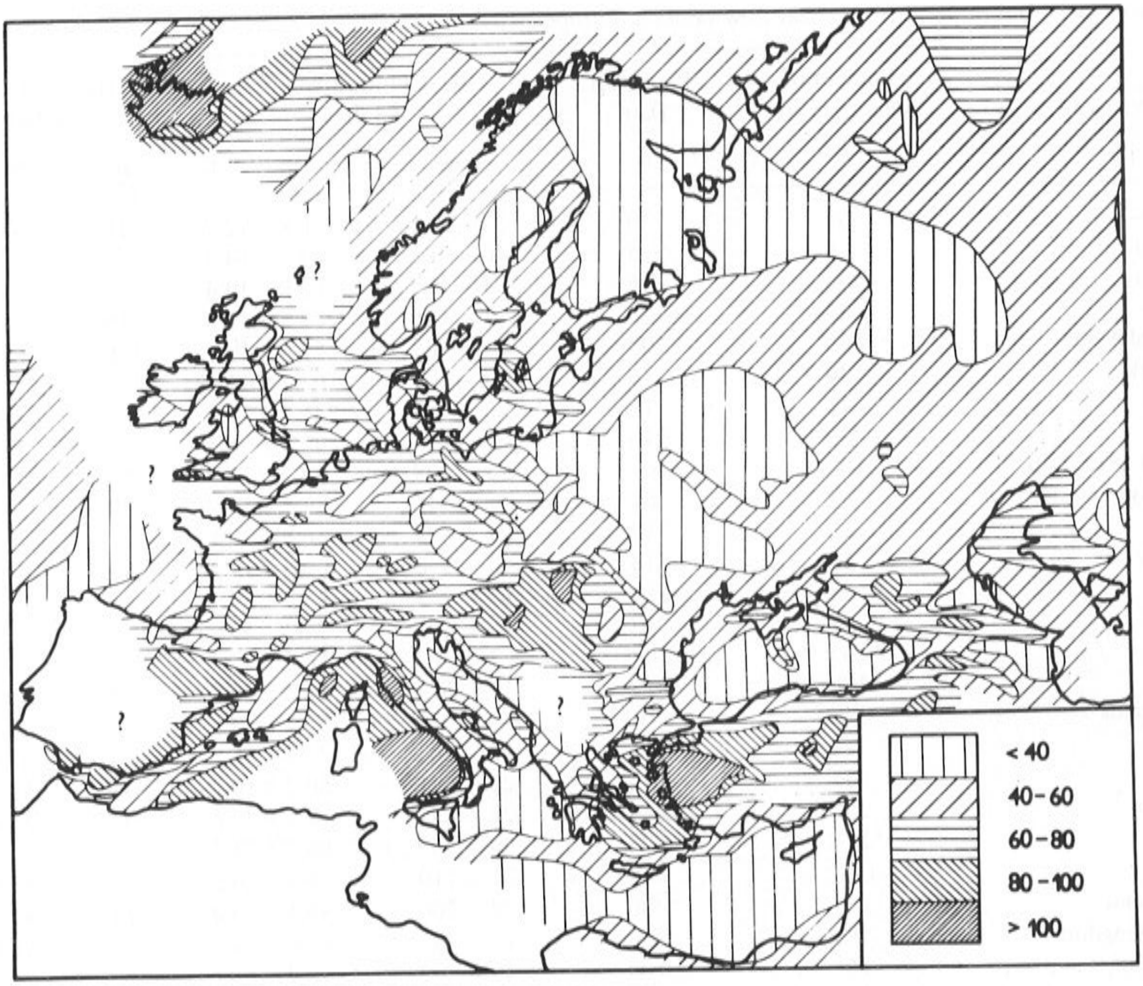

Figure 4 — Simplified heat flow map of Europe adapted from the 1:6,000,000 multicolours version (CERMÁK and HURTIG, Eds., 1979).

HEAT FLOW AND AGE

There are few variations of the surface heat flow with age in the Precambrian realm (35-45 mWm^{-2}) and most of the increase in the heat flow (from 40 to 100 mWm^{-2}) took place within the last 500 million years. The original analysis of continental heat flow and its dependence on age (Polyak & Smirnov, 1968; Hamza & Verma, 1969) was later re-examined (Chapman & Furlong, 1977) with the use of a considerably greater number of data. The generalized relationship obtained is shown in Fig. 6 as a shaded strip together with all the available results of heat flow versus age relationship published for Europe. It can be seen that most of the European data are systematically about 8-10 mWm^{-2} lower than a representative "all continent" curve, except for the European platform, Bohemian Massif and various Variscan (Hercynian) values. If this departure is generally true for the whole of Europe, it can be concluded that this is the most prominent example of the difference reported by Chapman & Furlong (1977), which is supposed to exist between Gondwana and Laurasia protocontinets.

However, the problem of relating heat flow and tectonic age is not so simple, see e.g. discussions by Rao et al. (1982), Morgan & Sass (1984), and a lot of may be systematically biases by various local disturbing effects or the statistically determined mean values may suffer from improper sampling. The relatively higher value for the East European Platform can be explained by a considerable amount of data from the Dniepro-Donetck Basin, an area of relatively elevated heat flow due to its local geological history. The increased mean value for the whole platform is thus the product of the uneven distribution, an imbalance caused by a non-typical area. Likewise, the values from the Bohemian Massif may also be relatively higher due to a certain revival of tectonic activity at depth during the Alpine orogenesis (Cěrmák, 1975). Anomalously high Variscan values reported by Chapman et al. (1979) for Central Europe

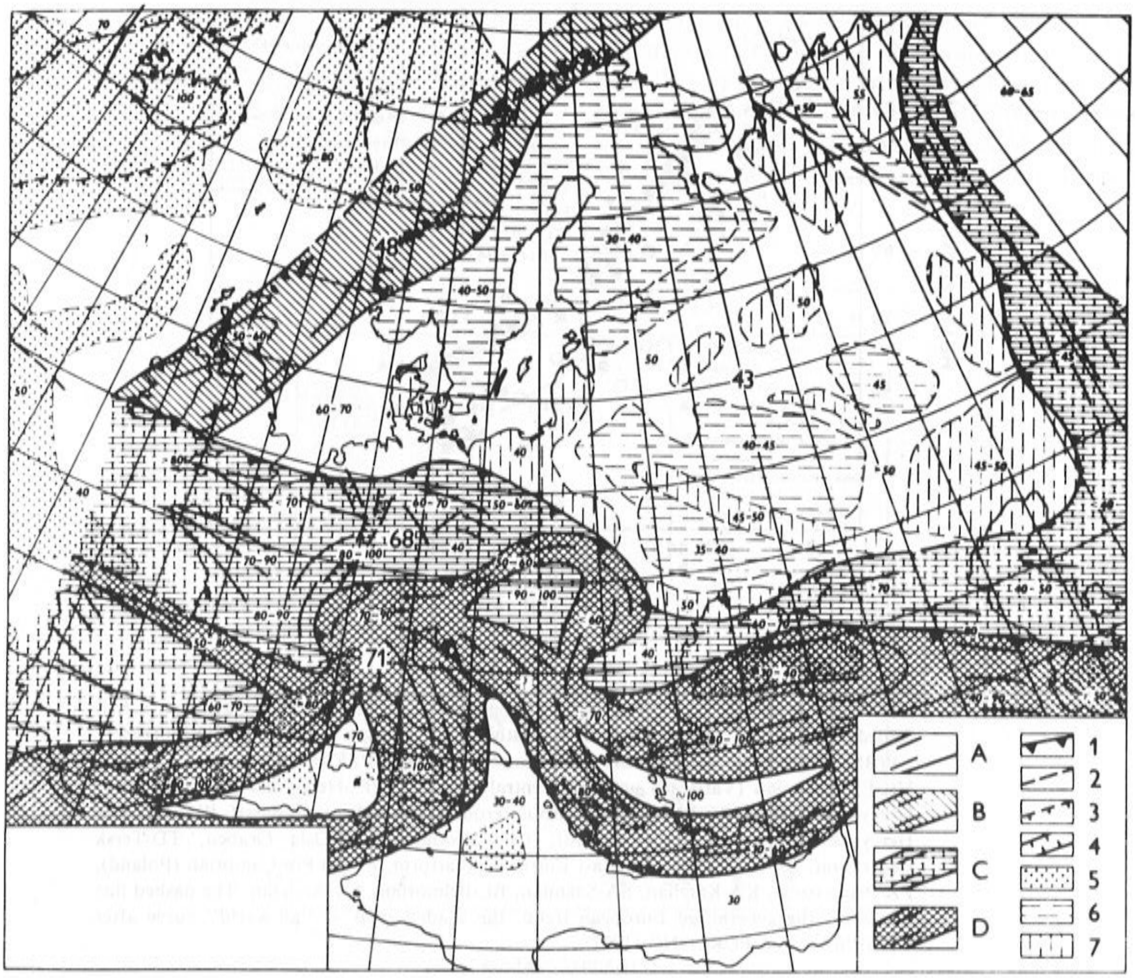

Figure 5 — Schematic tectonic setting of the European continent together with characteristic heat flow values for major tectonic or geological units (in mWm^{-2}). Tectonic pattern adapted from DOTT and BATTEN (1971) and KHAIN and LEONOV, Eds., 1979). Explanations: A — Precambrian cratonic area, B — Early Paleozoic (Caledonian) mobile belts, C — Late Paleozoic (Variscan) Mobile belts, D — Cenozoic (Alpine) mobile belts, 1 — Thrust faults and nappe structures, 2 — Transform faults, 3 — Limits of the Mid-Atlantic Ridge System, 4 — Rifts faults (Late Cenozoic), 5 — Oceanic or suboceanic type crust, 6 — Zones of elevated basement, 7 — Zones of depressed basement.

and by Majorowicz (1979) for Poland seem to fit this explanation, too. The close proximity of these sites to the regions of the Alpine system is evident. The positions of the Variscan data from the USSR (Kutas et al., 1976) are lower compared with the above points, but slightly higher compared with the general trend of the European curve since the distance from the Alpine structures is greater for these regions. It is worth mentioning in this connection that there is only a slight difference in the mean heat flows between Variscan and Alpine systems (58 to 61 mWm^{-2}), see Table 2.

HEAT FLOW AND CRUSTAL THICKNESS

As crustal radioactivity generates a substantial part of the heat flow, one might expect thick crust to correspond to the regions of increased surface heat flow, while low heat flow should be typical of the regions of a thinned crust. However, a comparison of the heat flow and the crustal thickness patterns of Europe suggests that many regions exhibit the opposite tendency (Cĕrmák, 1979). The Ukrainian and the Baltic shields, most of the East European Platform, the Bohemian Massif, the Urals, all have crustal thickness of about 40 km and more and very low to subnormal heat flow of 40-50 mWm^{-2}. On the other hand, a higher heat flow of up to 100 mWm^{-2} is typical of the Pannonian Basin or the Upper Rhinegraben, which display an unusually thin crust of 25 km or less. An inverse relation between the heat flow and the crustal thickness based on detailed regional studies (Fig. 7) was reported by Cĕrmák (1976) for Czechoslovakia, by Majorowicz (1978) for Poland, by Kutas (1979) for the Ukrainian shield, and by Veliciu & Demetrescu (1979) for Romania. This relation may also be valid in Spain (Albert-Beltrán, 1979). It must be admitted, however, that there are two areas which do not fit the above inverse relation: the Alps, where heat flow reaches 70-80 mWm^{-2} and the crust is considerably depressed into the

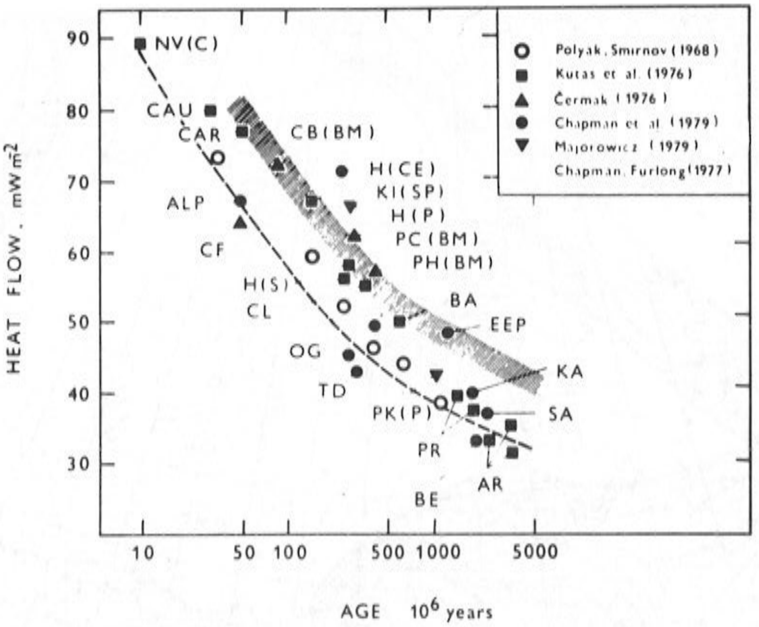

Figure 6 — Heat flow versus age in Europe. NV(C)-Neogene volcanic areas of the Caucasus, CAU-folded units of the Caucasus, CAR-Carpathians, ALP-Alps, CF-Carpathian Foredeep, CB(BM)-Cretaceous Basin of the Bohemian Massif, KI(SP)-Kimmerian (Scytian) Plate, H(CE)-Hercynian (Variscan) units of Central Europe, H(P)-Hercynian (Poland), H(S)-Hercynian (USSR), PC(BM)-Permo-Carboniferous of the Bohemian Massif, PH(BM)-Pre-Hercynian of the Bohemian Massif, CL-Caledonian, OG-Osla Graben, TD-Tersk Depression, BA-Baikalian, EEP-East European Platform, PK(P)-Pre-Cambrian (Poland), PR-Proterozoic, KA-Karelian, SA-Saamian, BE-Belmorian, AR-Archenn. The dashed line represents the generalized European trend, the shaded strip — "all-world" curve after CHAPMAN and FURLONG (1977).

upper mantle (Moho depth of 40-50 km), and the Black Sea region, with the sub-oceanic crust only 20 km thick characterized by low heat flow (30-40 mWm^{-2}). In both cases the application of geological corrections to the observed heatflow helps improve the studied relationship (Cěrmák, 1979), but the whole problem deserves much more investigation.

The problem of heat flow — crustal thickness relationship is likely to be directly connected with the role of the heat supply from the deeper parts of the mantle as the energy source during the tectonic evolution. If the negative relation between both parameters is generally true, then the crustal radioactivity cannot play a decisive role in the regional character of the surface heat flow, but it must be the heat flow from the upper mantle that maintains it. The areas fo a thinner crust are usually younger in origin than the relatively colder areas with a thick crust which belong to the oldest tectonic units. In the hyperthermal regions with a very high surface geothermal activity, high crustal temperatures associated with the increased heat flow from depths may cause some subcrustal erosion, i.e. a change of the crustal material into denser rocks having upper mantle properties. Crustal thickening in the younger mountains was caused by interthrusting in orogenes and the elevated heat flow may thus be a transient phenomenon. An important question to be solved is the extent to which the position of the Mohorovicić discontinuity is time dependent. While in older areas the crust might have grown thicker due to cooling, the thick crustal bulges below the young mountain may gradually be reduced by the process of basification.

CRUSTAL TEMPERATURES

To be able to compare the various tectonic provinces and to rate them according to their deep temperatures, the exponential distribution of heat sources $A(z) = A_0 \exp(-z/D)$ was used and the simple one-dimensional, conductive, steady-state geotherms were calculated for all major tectonic units (Cěrmák, 1982a):

$$T(z) = T_0 + \frac{q_0 z}{k} + \frac{A_0 D^2}{k} (1 - e^{-z/D}),$$

where T_0 is the surface temperature, q_0 is the reduced heat flow ($q_0 = Q - A_0 D$), and A_0 is the surface heat generation. The following parameters were used: $A_0 = 2 \mu Wm^{-3}$, $D = 10$ km, $k = 2.5\ Wm^{-1}K^{-1}$. which represent the mean values of a broad interval, but which may well serve as a first approximation. For higher surface radioactivity one has to suppose smaller D to avoid too high radioactivity of the lower crust. With the above parameters the characteristic heat production is $0.7 \mu Wm^{-3}$ at 10 km, $0.3 \mu Wm^{-3}$ at 20 km and

$0.1\mu Wm^{-3}$ at 30 km, which is in good agreement with the data reported.

Thermal conductivity generally decreases with increasing temperature, i.e. with increasing depth in the crust. Lower conductivity causes higher temperatures at all depths, but within reasonable limits of the existing values of conductivity, this effect is usually smaller than our uncertainty in both the radioactivity and surface heat flow. For each tectonic province the limits of the computed temperatures were determined (Table 2) for the minimum and maximum values of the surface heat flow (mean value ± standard deviation). In view of the inverse relation between the heat flow and the crustal thickness, the higher temperatures were attributed to the thinner crust and vice versa, the lower temperatures to the thicker crust. Relatively low temperatures (350-500°C) at the Mohorovicić discontinuity at a depth of 45-50 km are to be expected beneath the Precambrian shields and the East European Platform. Higher Moho temperatures of 500-600°C were calculated for the Paleozoic folded units such as the Bohemian Massif or the Ural Mountains at a depth of 35-45 km. Local, temperature maxima of 600-700°C seem to exist in the zones of a weakened crust and/or in the areas of deep faults, which manifest themselves by a relatively higher heat flow on the surface (up to 70 mWm^{-2}). Very high crustal temperatures ($T_M \sim 800$—1000°C) are probable in the hyperthermal regions, such as the Pannonian Basin or Upper Rhinegraben, characterized by high surface heat flow (over 100 mWm^{-2} and a thin crust (25 km)). The regional distribution of deep temperatures in Europe at a depth of 40 km is shown in Fig. 8.

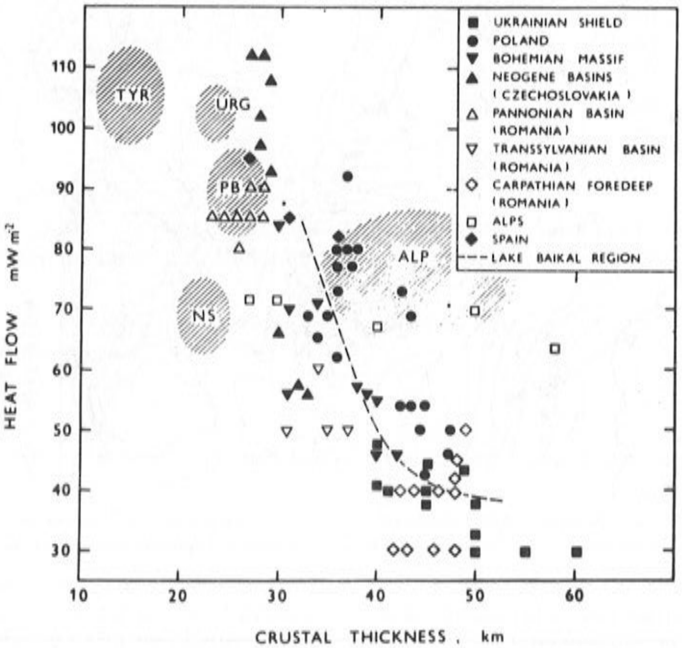

Figure 7 — Heat flow versus crustal thickness in Europe. Experimental data reported by Kutas (1979) for the Ukrainian shield, Majorowicz (1978) for Poland, Cěrmák, (1976) for the Bohemian Massif and the Neogene depressions in Western Carpathians, Veliciu and Demetrescu (1979) for Romania, Rybach et al. (1977) for the Alps, Albert-Betrán (1979) for Spain. For comparison, the dashed line shows the trend of similiar data from the Lake Baikal region (Lysak, 1976). Shaded areas show the range of typical values for the Tyrrhenian Sea (TYR), Upper Rhinegraben (URG), Pannonian Basin (PB). North Sea (NS) and the Alps (ALP).

MOHO HEAT FLOW

The value of the heat flow on the crust-upper mantle boundary, the so-called Moho heat flow (Q_M), determines the energy budget of the upper mantle deep processes. In order to evaluate its value, it is necessary to subtract the crustal contribution due to radioactivity (A(z)) from the surface heat flow (Q), the effect of other possible heat sources within the crust is usually negligible, i.e. $Q_M = Q - \int_0^{z_M} A(z)\,dz$, where z_M is the Moho depth.

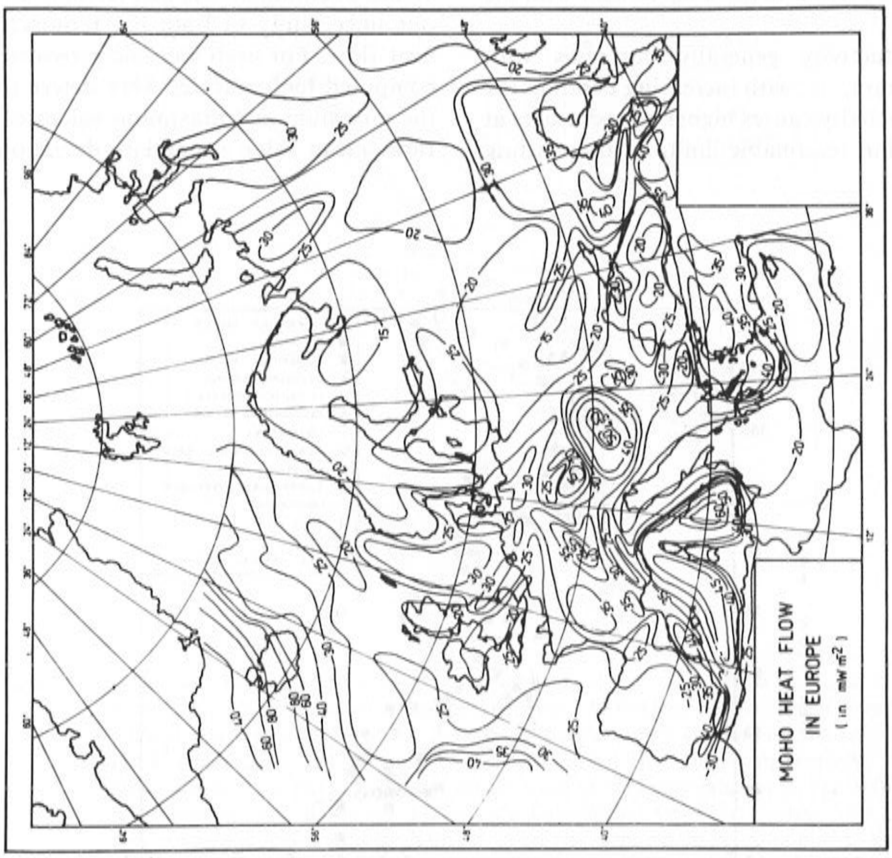

Figure 9 — Regional distribution of Moho heat flow in Europe.

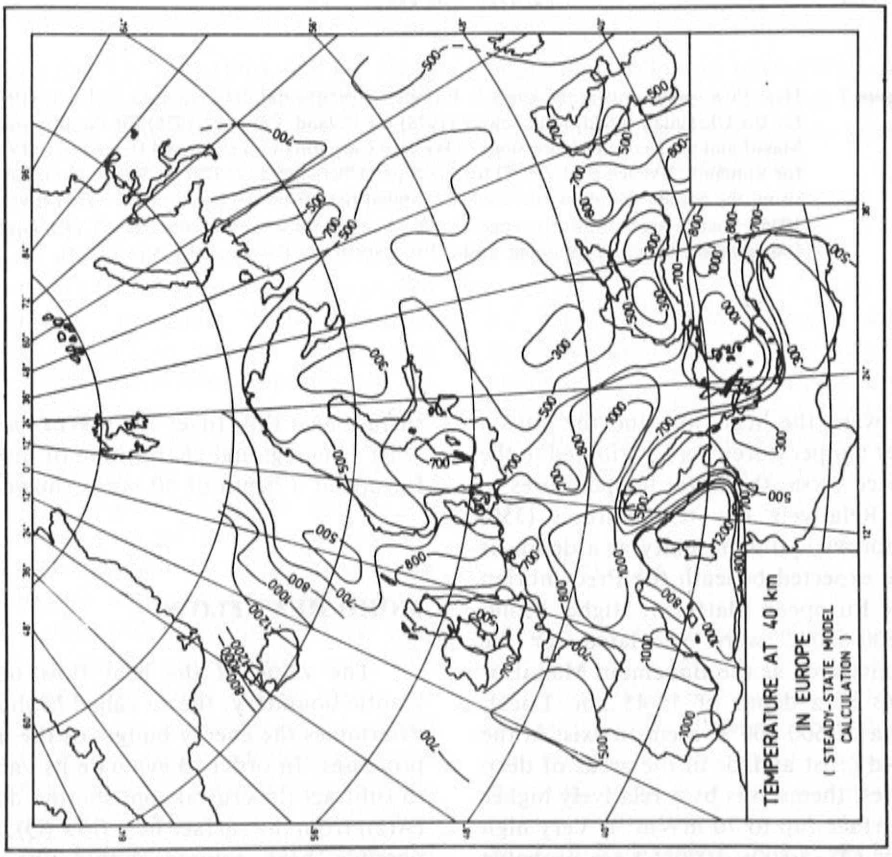

Figure 8 — Regional distribution of calculated temperatures at a depth of 40 km in Europe.

Table 2 – Mean Heat Flow and Crustal Thickness together with Calculated Moho-temperatures and Temperatures at 40 km Depth for Major Geological Features in Europe.

Geological Feature	Heat Flor (mWm^{-2}) Mean	Heat Flor (mWm^{-2}) Range[1]	Crustal Thickness (km) Mean	Crustal Thickness (km) Range[1]	Temperature[2] at Moho Min.	Temperature[2] at Moho Max.	Temperature[3] at 40 km Min.	Temperature[3] at 40 km Max.
Baltic and Ukrainian Shields	39	31 – 47	42	37 – 47	280	480	250	510
East European Platform	44	37 – 51	42	38 – 46	390	550	350	570
Palec-Europe (Caledonian)	48	43 – 53	35	30 – 41	440	400	440	600
Western Siberia	54	48 – 60	38	35 – 42	540	640	520	7200
Meso-Europe (Hercynian)	68	56 – 80	30	28 – 33	540	740	650	1040
Ural	49	43 – 55	43	40 – 46	500	640	440	640
Neo-Europe (Alpine)	71	55 – 87	16	27 – 41	650	850	630	1150
Hyperthermal Basins[4]	97	79 – 115	25	22 – 28	730	900	1020	1600?

[1] Range calculated as the mean value ± standard deviation.

[2] For the calculation of the Moho-temperature the following combinations were used : minimum heat flow – maximum crustal thickness and/or maximum heat flow – minimum crustal thickness, respectively. The range is thus narrower than in case of T_{40}.

[3] Minimum and maximum heat flow used together with the depth of 40 km.

[4] Pannonian Basin, Upper Rhinegraben.

To estimate the total crustal radioactivity, one has to create various models and to check their validity by independent criteria. The radioactivity decreases with depth, but the use of the simple exponential model of heat sources within the entire crust (Lachenbruch, 1968) may be problematic, as it gives rather low heat production values in the lower crust and thus probably unreliably high temperatures at the Mohorovicić discontinuity. The step model of the crust (Roy et al., 1968) defining the crust as a multilayered medium of individual layers of constant radioactivity corresponding to typical crustal rocks is schematic but provides a better basis for the Moho heat flow estimate. The problem of determining a reasonable characteristic value of the radiogenic heat generation for each layer is then crucial. Some help may be sought in the deep seismic sounding data and the experimental relationship between heat production and seismic velocity (decreasing radioactivity with increasing velocity) originally reported by Rybach (1973). The data of explosion seismology thus provide material for both the specification of the crustal structure and its subdivision into individual layers and for a rough estimate of the heat generation value for each layer.

A scheme of the Moho heat flow pattern in Europe (Fig. 9) (Cěrmák, 1982a) was proposed with the help of the surface heat flow field represented by mean 2°x2° grid elements values taking into account the tectonic setting and a possible effect of the appropriate corrections on the measured heat flow and completed by a crustal thickness map. For the evaluation of the heat production distribution, the deep seismic sounding data on the depth distribution of the v_p velocities published by P. Giese, A. Guterch, C. Morelli, C. Prodehl, D. Prosen, V.Z. Ryaboy, V.B. Sollogib, A. Stein, L. Steinmetz, G. Szenas, B.S. Volvovskiy, I.S. Volvovskiy, and many others, were used, averaged in the same 2°x2° coordinate network and then converted to the heat generation values using Rybach's (1973) curve.

While beneath the shield, even if the crustal rocks are considerable depleated in radioactivity, the heat flow from the upper mantle cannot exceed 15-20 mWm^{-2}, the normal Moho heat flow in the platform areas, Paleozoic folded units and in the Cenozoic mountain belts varies from 20-25 to 30-35 mWm^{-2}, respectively. The hyperthermal areas of the Alpine intramontane depressions or of the young rift valleys must have a high Moho heat flow of a minimum of 40-50 mWm^{-2}, even if the crustal rocks are rich in radioactivity (which is not likely). There must be thus a substantial regional difference in the upper mantle heat flow contribution, attaining as much as 30-40 mWm^{-2}. Still higher excesses may exist in the region of suboceanic or oceanic type crust (Tyrrhenian Sea, Mid-Atlantic Ridge). Such a regional variation in the energy outflow represents an important parameter in the tectonic evolution as well as a critical limitation on the geophysical studies of the deep-seated processes.

HEAT FLOW AND THE LITHOSPHERE THICKNESS

A geothermal model of the lithosphere, in which the surface heat flow corresponds to the sum of the heat flowing into the lithosphere at its base plus the heat generated within the crust, was proposed (Chapman & Pollack, 1977). For such a model deep one-dimensional temperature distribution was calculated as a function of the surface heat flow value. The calculated geotherms were used in combination with the mantle melting relations to estimate the top of a seismic low velocity channel (Cěrmák, 1982b). This channel may characterize the passage between the solid lithosphere and the more viscous asthenosphere, the relatively sharp decrease of the seismic velocity may relate to the fact that the existing temperatures at this depth reach or are close to the melting temperature of the surrounding rocks. The calculated temperature-depth curves for the standard crustal thickness $z_M = 35$ km are shown in Fig. 10 together with the melting relations adopted after Chapman et al., (1979). For the evaluation of the lithosphere thickness, the intersection of the temperature curve with the "mixed volatile" mantle solidus was used. All the European territory was subdivided into regular 4°x4° latitude-longitude grid elements and the corresponding lithosphere thickness was determined in each such element. Since the deep calculated temperature slightly depends on the actual depth of the Mohorovicić discontinuity, the mean crustal thickness in each grid element was taken and incorporated into the model calculation. For a thicker crust, higher upper mantle temperatures are obtained and for a thinner crust, lower temperatures are found. The actual fan of geotraverses is thus narrower in comparison with that for the standard crustal thickness because of the obtained negative relationship between the surface heat flow and the crustal thickness (see above).

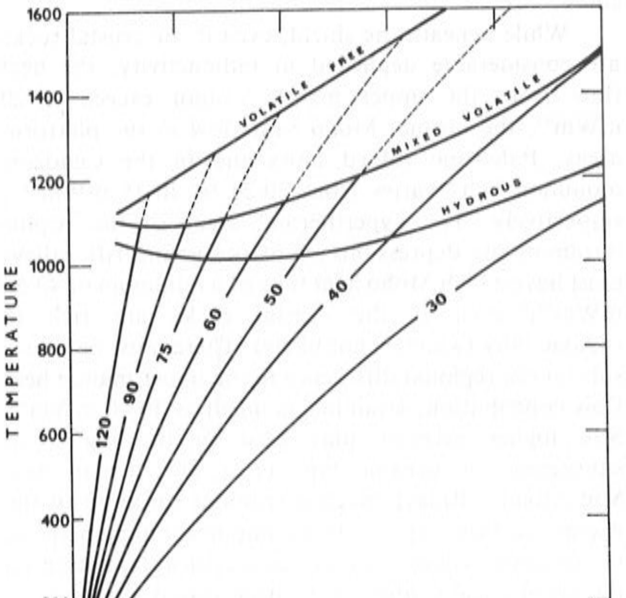

Figure 10 —Geotherm family for the continental lithosphere (Cěrmák, 1982b) together with melting relations after (Chapman et al., 1979). Individual curves are labelled in surface heat flow (mWm^{-2}).

By interpolating the individual grid data the regional pattern of the lithosphere thickness in Europe was projected (Fig. 11). The projected thickness varies from less than 50 km to more than 200 km. The thick lithosphere corresponds to both shields and a greater part of the East European Platform, i.e. to the oldest and the most stable tectonic regions forming the European craton, and to the Eastern part of the Mediterranean Sea. The thinnest lithosphere exists in the North Atlantic along the axis of the Mid-Atlantic Ridge and in the young Alpine-Carpathians belt of Neo-Europe. Thin lithosphere also characterizes the western part of the Mediterranean Sea, particulary the Tyrrhenian Sea. Thus the lithospheric thickness directly corresponds to the intensity of the deep-seated processes in the upper mantle and is closely connected with the age of the crustal stabilization in its tectonic evolution. The thickness pattern obtained seems to correlate well with Ádám's (1978) magnetotelluric data on the position of the high electric conductivity layer, which is supposed to be upper part of the asthenosphere, its depth varies from loss than 60 km below the areas of high heat flow (Pannonian Basin, South Caspian Depression) to more than 200 km below the stable platform areas of low surface geothermal activity. Moreover, seismological data on the Rayleigh wave dispersion (Calcagnile & Panza, 1980, Calcagnile et al., 1980) correspond also fairly well to the present results even though it is possible that the actual lithospheric thickness beneath the hyperthermal regions, such as the Upper Rhinegraben, can be as small as 40-50 km.

As there are several concepts of the nature of the lithosphere/asthenosphere boundary, based on different geophysical data and on different selected parameter and its behaviour with depth, such as seismological, geothermal, magnetotelluric or rheological, the projected lithosphere thickness may sometimes vary. Further the position of the lithosphere/asthenosphere boundary needs not necessarily be constant in time, but may either propagate downwards in the stable steadily cooling areas (shields), or move upwards in areas of increasing heat flow supply from greater depth (rift zones, young sedimentary basins) and in places, where the lithospheric plate was buckling or pushed into underlaying more viscous basement (subduction zones). The latter case may relate the young mountain ranges, such as e.g. the Alps, which are characterized by a deep reaching lithospheric root, but at the same time also by a high surface heat flow. Therefore in the Alpine realm of Europe, the above geothermal assessment of the lithosphere thickness may be problematic.

TWO-DIMENSIONAL TEMPERATURE PROFILES

With the data on crustal and lithosphere structure made available by explossing seismology, deep temperature distribution was calculated along five long-run geotraverses in Central and Eastern Europe, crossing all major tectonic units of Precambrian craton and of Variscan and Alpine fold belts (Cěrmák, & Bodri, 1986) (Fig. 12). A two-dimensional numerical solution of the steady-state equation of heat conduction in an inhomogeneous medium was obtained by means of the finite differences method. The relations between the surface heat flow, Moho heat flow, thermal conductivity and the distribution of heat sources was described by a linear algebraic system, which was solved by means of the iterative method of successive overrelaxation. The least squares techniques was applied to overcome the non-uniqueness and instability of such a solution (Stromeyer, 1984; Safanda, 1985). To demonstrate here the procedure used and to present an example of such a calculation, the deep temperature distribution along the southern part of the East European geotraverse EEGT 1 is shown in Figs. 13 and 14. This section includes the Alpine molasse, Bohemian Massif, Sudetes, Fore-Sudetic Monocline, Teisseyre-Tornquist zone and the adjacent part of the East European Platform. The results of deep seismic sounding (Sollogub et al., 1980) were employed to define the crustal block structure and the distribution of the seismic velocities. Rybach & Buntebarth's (1984) formula $A = f(v_p)$ was then applied together with corresponding corrections for in situ conditions involving temperature and pressure dependences of v_p (Čermák, 1988) to convert characteristic seismic velocities of each block into a heat generation value. It was supposed that the heat production exponetially decreased with depth in each block, $A(z) = A_0 \exp(-z/D)$, the logarithmic decrement D was authomatically calculated to ensure the continuity of A(z) in the whole vertical section. Thermal conductivity is temperature dependent $k = k_0(1 + CT)^{-1}$, each block is assigned values of k_0 and C

The two-dimensional solution of the heat conduction equation requires the knowledge of the conditions on the lower boundary, which is usually not the case. The problem is thus ill-posed and the inverse problem must be solved first, in which the observed surface heat flow, Q_0, is used to evaluate the heat flow from the depth. For this purpose, the surface heat flow was assumed to be the sum of two components: the crustal contribution due to its heat sources, Q, and the mantle (Moho) heat flow, Q_M. By repeated calculations of the surface heat flow corresponding to the model, Q_B, starting with an arbitrary value of Q_M and successively correcting the calculated Q_M-value by the difference $(Q_0 - Q_B)$, we were able to assess the conditions on the lower boundary of the model within a certain limit of accuracy. Several slightly different approaches to the problem were tested. They involved the regularization process to limit the maximum variation of Q_M per unit distance, optimalization and redistribution of heat sources in the uppermost crust, again limited by the chosen maximum variation of additional heat sources per unit volume (Safanda, 1985), and the application of the empirical relationship between surface heat flow and the near surface heat production and between reduced and mean surface heat flows (Čermák, & Bodri, 1986) to rate the upper crust radioactivity.

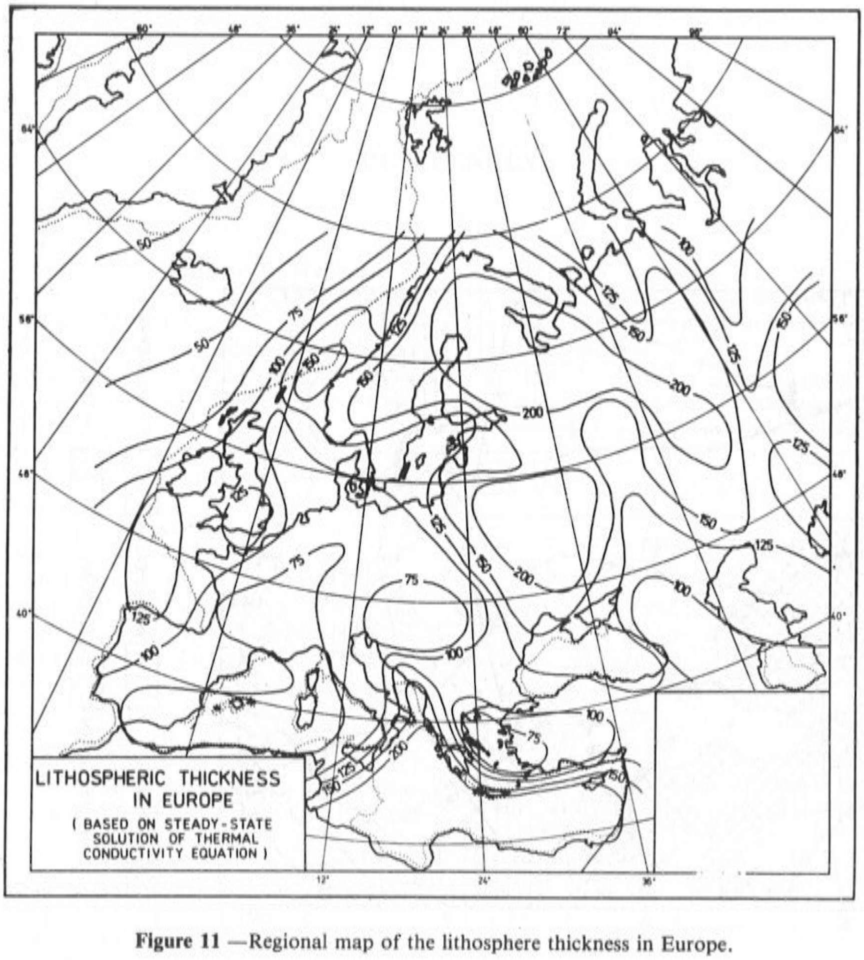

Figure 11 —Regional map of the lithosphere thickness in Europe.

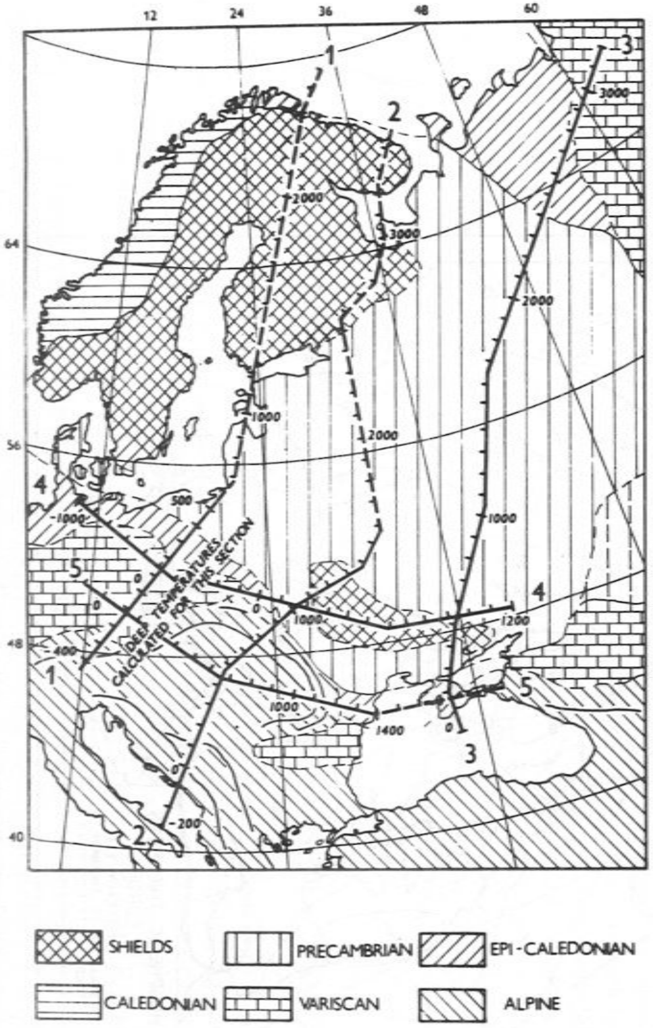

Figure 12 —Simplified tectonic pattern of Central and Eastern Europe together with the position of five geotraverses along which the deep temperatures were calculated (solid line), broken line shows the proposed but not yet finished parts of geotraverses. An example of the performed temperature calculation along the EEGT 1 is given in Figures 13 and 14.

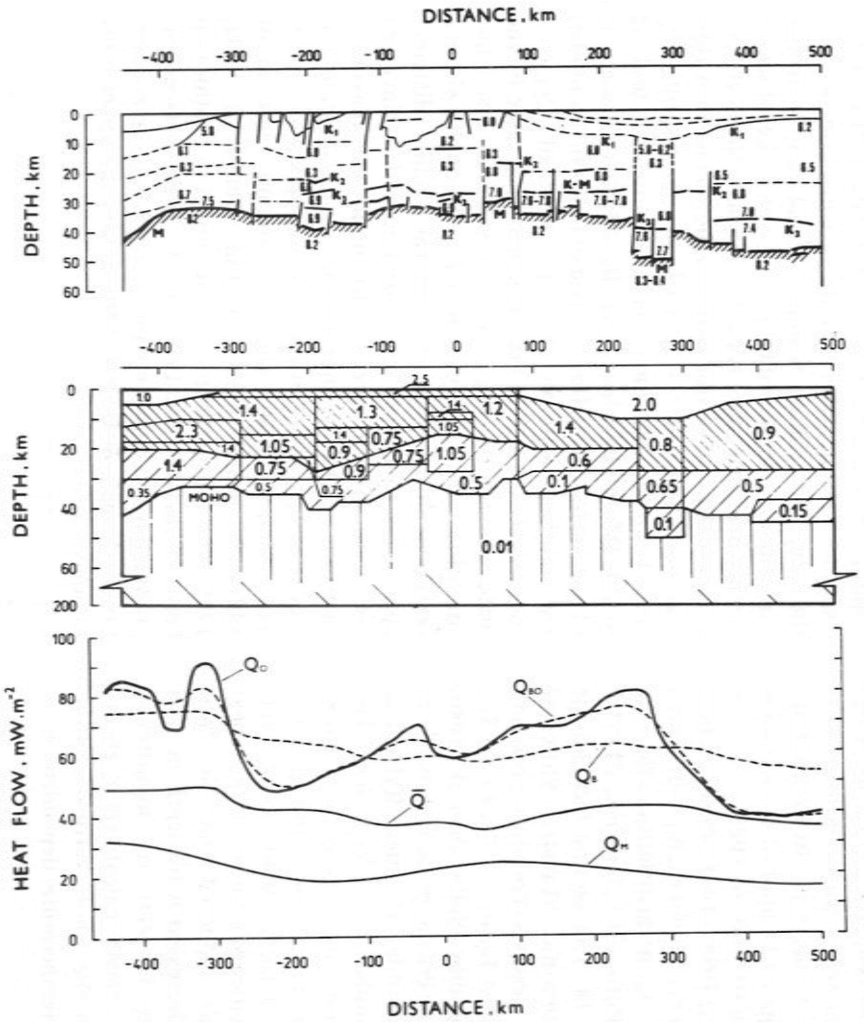

Figure 13 —Top: Schematic seismotectonic model of the geotraverse EEGT 1 based on deep seismic sounding data. The model shows the seismic velocity distribution (in km.s^{-1}) and the principal crustal discontinuities K_1, K_2 and K_3, and M — Moho surface.

Mid: Derived block structure of the Earth's crust with characteristic heat production values (in μWm^{-3}).

Bottom: Observed and calculated heat flow along the geotraverse, Q_O — observed surface heat flow, Q_M — Moho heat flow, Q — crustal contribution, Q_B — calculated surface heat flow prior to heat sources in the uppermost crust were optimized, Q_{BO} — calculated surface heat flow for a model with optimized heat sources.

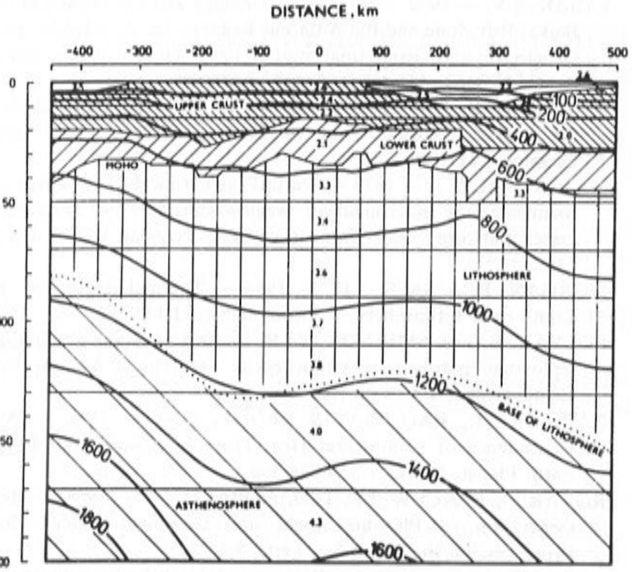

Figure 14 —Calculated deep temperature distribution along the EEGT 1 geotraverse (in °C) together with characteristic thermal conductivities in individual layers (in $W.m^{-1}K^{-1}$). Note, that the projected lithosphere thickness below the Alps in the southernmost sector of the geotraverse may disagree with the results of other investigators, see text.

The results of the performed two-dimensional temperature profiling confirmed the data on the deep temperature distribution and the Moho heat flow obtained earlier. The Mohorovicić discontinuity is definitely not an isothermal surface, neither is the outflow of heat from the upper mantle constant, but both parameters may vary in broad ranges. The Moho temperature can be as low as 350°C in the shield areas, however, it can exceed 900°C in some young intramontane depressions or rift structures, regional variations of the Moho heat flow can range from 15-20 to 40-60 mWm^{-2}, and its value reflects the tectonic stabilization of the lithosphere. Surface heat flow is the primary parameter for the deep temperature calculation, the uncertainty in its correct determination thus severely limits the credibility of any temperature modelling. In a prevailing part of all investigated geotraverses the shapes of the Q_0 and the Q_M courses are nearly identical. This parallelism is quite typical and suggests that the mantle heat flow contribution is decisive for the observed surface geothermal activity. The crustal contribution shows smaller regional variations and amounts to approximately 20-30 mWm^{-2}, except in areas of deep mountain roots of granitic or metamorphosed rocks of relatively higher radioactivity. Temperatures at a 100 km depth vary from 700-800°C to more than 1400°C, and the results clearly confirm the possible existence of the asthenosphere at depths as shallow as 60-70 km in areas of high heat flow, and deeper than 150-200 km in areas of low to very low surface heat flow. However, the present purely conductive model is applicable to regions with temperatures below 1100-1200°C since it does not consider the effects of partial melting and convection. At higher temperatures the effective thermal conductivity rapidly increases, and the temperature gradient may drop considerably.

REFERENCES

ADAM, A. — 1978 — Geothermal Effects in the Formation of Electrically Conducting Zones and Temperature Distribution in the Earth. Phys. Earth Planet. Int., **17**:21-28.

ALBERT-BELTRÁN, J.F. — 1979 — Heat Flow and Temperature Gradient Data from Spain. In: V. CÉRMÁK & L. RYBACH. Eds.: Terrestrial Heat Flow in Europe, 261-266. Springer Verlag, Berlin, Heidelberg and New York.

ANONYMOUS — 1962 — Carte tectonique internationale de l'Europe 1:2,500,000. C.G.M.W. Subcommission for the Tectonic Map of the World, Moscow.

ANONYMOUS — 1971 — International Geological Map of Europe and the Mediterranean Region, 1 500,000. Bundesanst. Bodeforsch. and UNESCO, Hannover.

CALCAGNILE, G., D'INGEO, F. & PANZA, G.F. — 1980 — The Lithosphere in South-eastern Europe: Preliminary Results. In: A. UDIAS and J.CHANNEL, Eds.: Evolution and Tectonics of the Western Mediterranean and Surrounding Areas, 231-236. Inst. Geografico Nacional, Spec. Publ. 201, Madrid.

CALCAGNILE, G. & PANZA, G.F. — 1980 — The LithosphereAsthonosphere System in the Italian Area. In: A. UDIAS and J. CHANNEL, Eds.: Evolution and Tectonic of the Western Mediterranean and Surrounding Areas, 225-230. Inst. Geografico Nacional, Spec. Publ. 201, Madrid.

CĚRMÁK, V. — 1975 — Temperature-Depth Profiles in Czechoslovakia and Some Adject Areas Derived from Heat Flow Measurements, Deep Seismic Sounding and Other Geophysical Data. Tectonophysics **26**:103-119.

CĚRMAK, V. — 1976 — Heat Flow Investigations in Czechoslovakia. In: A. ÁDÁM, Ed.: Geoelectric and Geothermal Studies (East-Central Europe, Soviet Asia), 314-324. Akademial Kiadó, Budapest.

CĚRMAK, V. — 1977 — Some Comments on the Effect of the Past Climatic Changes on the Underground Temperature Field. Publ. Geophys. Inst. Pol. Acad. Sci., A-3(103):45-56.

CĚRMAK, V. — 1979 — Heat Flow Map of Europe. In: V. CĚRMÁK & L. RYBACH, Eds.: Terrestrial Heat Flow in Europe, 340. Springer Verlag, Berlin, Heidelberg and New York.

CĚRMAK, V. — 1982a — Crustal Temperature and Mantle Heat Flow in Europe. Tectonophysics, **83**:123-142.

CĚRMAK, V. — 1982b — Regional Pattern of the Lithosphere Thickness in Europe. In: V. CĚRMÁK & R. HAENEL, Eds.: Geothermics and Geothermal Energy, 1-10. E. Schweizerbart'sche Verlagsbuch-handlung, Stuttgart.

CĚRMAK, V. — 1988 — Crustal Heat Production and Mantle Heat Flow in Central and Eastern Europe. Tectonophysics (in press).

CĚRMAK, V. & BODRI, L. — 1986 — Two-dimensional Temperature Modelling along Five East-European Geotraverses. J. Geodynamics, **5**:133-163.

CĚRMÁK, V. & HURTIG, E. — 1977 — Preliminary Heat Flow Map of Europe (1: 5,000,000). Map and Explanatory Text. Geofyz. úst. CSAV, Praha and Zentralinst. f. Physik d. Erde, AdW DDR, Potsdam, 58 pp.

CĚRMÁK, V. & HURTIG, E. — 1979 — Heat Flow Map of Europe. In: V. CĚRMÁK & L. RYBACH, Eds.: Terrestrial Heat Flow in Europe, enclosure. Springer Verlag, Berlin, Heidelberg and New York.

CĚRMÁK, V. & RYBACH, L. — 1979 — Terrestrial Heat Flow in Europe. Springer Verlag, Berlin, Heidelberg and New York, 328 pp.

CHAPMAN, D.S. & FURLONG, K.P. — 1977 — Continental Heat Flow: Age Relationship. EOS Trans. Am. Geophys. Union, **58**:1240.

CHAPMAN, D.S. & POLLACK, H.N. — 1975 — Global Heat Flow: A New Look. Earth Planet. Sci. Lett., **28**:23-32.

CHAPMAN, D.S. & POLLACK, H.N. — 1977 — Regional Geotherms and Lithospheric Thickness. Geology, **5**, 265-268.

CHAPMAN, D.S., POLLACK, H.N. & CĚRMAK, V. — 1979 — Global Heat Flow with Special Reference to the Region of Europe. In: V. CĚRMÁK & L. RYBACH, Eds.: Terrestrial Heat Flow in Europe, 41-48. Springer Verlag, Berlin, Heidelberg and New York.

CIARANFI, N., LODDO, M. & MONGELLI, F. — 1973 — Paleoclimatic Effect on the Geothermal Gradient in Never Ice Covered Mediterranean Regions. Rev. Ital. Geofis., **22**:1-7.

DOTT, R.H. Jr. & BATTEN, R.L. — 1971 — Evolution of the Earth. MsGraw Hill Comp., New York, 649 pp.

ERICKSON, A.J. — 1970 — The Measurement and Interpretation of Heat Flow in the Mediterranean and Black Seas. Thesis Mass. Inst. Technol. and Woods Hole Ocean. Inst., 272 pp.

GRUMBT, E., LUDWIGM, A: & MEIER, R. — 1976 — Tektonische Bruch-störungen, 1:6,000,000. In: K.G. JUBITZ, Ed.: Materialen zum tektonischen Bau von Europa, Veröff. Zentralinst. Phys. d. Erde, Vol. 47, Potsdam.

HAENEL, R. & ZOTH, G. — 1973 — Heat Flow Measurements in Austria and Heat Flow Maps of Central Europe. Z. Geophys., **39**:425439.

HAMZA, V.M. & VERMA, R.K. — 1969 — The Relationship of Heat Flow with Age of Basement Rocks. Bull. Volcanol., **33**:123-152.

KHAIN, V.E. & LEONOV, Yu.G., Eds. — 1979 — Carte tectonique de l'Europe et des régions avoisinantes, 1:10,000,000. Dir. Gén. Géodesie, Cartogr., Conceil Ministres de l'URSS, Moscow.

KUTAS, R.I. — 1979 — A Geothermal Model of the Earth's Crust on the Territory of the Ukrainian Shield. In: V. CÉRMÁK and L. RYBACH, Eds.: Terrestrial Heat Flow in Europe, 309-315. Springer Verlag, Berlin, Heidelberg and New York.

KUTAS, R.I., LUBIMOVA, E.A. & SMIRNOV, Ya.B. — 1976 — Heat Flow Map of the European Part of the URSS and Its Geological Interpretation. In: A. ÁDÁM, Ed.: Geoelectric and Geothermal Studies/East-Central Europe, Soviet Asia/, 443-449. Akademiai Kiadó, Budapest.

LACHENBRUCH, A.H. — 1968 — Preliminary Geothermal Model of the Sierra Nevada. J. Geophys. Res., **73**:6977-6989.

LYSAK, S.V. — 1976 — Heat Flow, Geology and Geophysics in the Baikal Rift Zone and the Adjacent Regions. In: A. ÁDÁM, Ed.: Geoelectric and Geothermal Studies/East-Central Europe, Soviet Asia/, 455-462. Akademiai Kiadó, Budapest.

MAJOROWCZ, J. — 1978 — Mantle Heat Flow and Geoisotherms for Major Tectonic Units in Central Europe. Pure Appl. Geophys., **117**:109-123.

MAJOROWICZ, J. — 1979 — Warunki geotermiczne i ich wplyw na rozmieszczenie nagromadzen weglowodorodow w zachodniej czesci platformy wschodnioeuropejakej. Przeglad Geol., **4**:232-238.

MORGAN, P. & SASS, J.H. — 1984 — Thermal Regime of the Continental Lithosphere, J. Geodynamics, **1**:143-166.

POLYAK, B.G. & SMIRNOV, Ya.B. — 1968 — Švyaz glubinnogo teplovogo potoka s tektonicheskim stroyeniem kontinentov. Geotektonika, **4**:3-19 (in Russian).

RAO, R.U.M., RAO, G.V. & REDDY, G.K. — 1982 — Age Dependence of Continental Heat Flow — Fantasy and Facts. Earth Planet. Sci. Lett., **59**:288-302.

ROY, R.F., BLACKWELL, D.D. & BIRCH, F. — 1968 — Heat Generation of Plutonic Rocks and Continental Heat Flow Provinces. Earth Planet. Sci. Lett., **5**:1-12.

RYBACH, L. — 1973 — Wärmeproduktionsbestimmungen an Gesteinen der Scweizerischen Alpen. Beitr. Geol. Schweiz, Geotech. Ser. 51. Kümerly und Frey, Bern, 43 pp.

RYBACH, L. & BUNTEBARTH, G. — 1984 — The Variation of Heat Generation, Density and Seismic Velocity with Rock Type in the Continental Lithosphere. In: V. CÉRMÁK. L. RYBACH & D.S. CHAPMAN, Eds.: Terrestrial Heat Flow Studies and the Structure of the Lithosphere. Tectonophysics, **103**:335-344.

RYBACH, L., WERNER, D., MUELLER, S. & BERSET, G. — 1977 — Heat Flow, Heat Production and Crustal Dynamics in the Central Alps, Switzerland. Tectonophysics, **41**:113-126.

SAFANDA, J. — 1985 — Calculation of Temperature Distribution in Two-dimensional Geothermal Profile. Stud. geoph. et geod., **29**:191207.

SOLLOGUB, V.B., GUTERCH, A. & PROSEN, D., Eds. — 1980 — Struktura zemnoy kori i verkhney mantiyi po dannim, geofizicheskikh issledovanyi. Naukova Dumka, Kiev, 208 pp (in Russian).

STROMEYER, D. — 1984 — Downward Continuation of Heat Flow Data by Means of the Least Squares Method. In: V. CĚRMÁK, L. RYBACH & D.S. CHAPMAN, Eds.: Terrestrial Heat Flow Studies and the Structure of the Lithosphere. Tectonophysics, **103**:55-66.

VELICIU, S. & DEMETRESCU, C. — 1979 — Heat Flow in Romania and Some Relation to Geological and Geophysical Features. In: V. CĚRMÁK & L. RYBACH, Eds.: Terrestrial Heat Flow in Europe, 253-260. Springer Verlag, Berlin, Heidelberg and New York.